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International Agreement Report

Assessment of RELAP5/MOD 2 Against Critical Flow Data From Marviken Tests JIT 11 and CFT 21

Prepared by
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

September 1986

Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Thermal-Hydraulic Code Assessment
and Application Program (ICAP)

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Östen Rosdahl
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ICAP

Assessment of RELAP5/MOD Against Critical
Flow Data from Marviken Tests JIT 11 and
CFT 21

ABSTRACT

RELAP5/ MOD2 simulations of the critical flow of saturated steam are reported together with simulations of the critical flow of subcooled liquid and a low quality two-phase mixture. The experiments which were simulated used nozzle diameters of 0.3 m and 0.5 m. RELAP5 overpredicted the experimental flow rates by 10 to 25 percent unless discharge coefficients were applied.

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Approved by

Eric Hellstrand

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EXECUTIVE SUMMARY

RELAP5/MOD2 simulations have been conducted to assess the critical flow model in RELAP5. The experiments chosen for the simulations were Marviken Jet Impingement Test (JIT) 11 (saturated steam flow) and Marviken Critical Flow Test (CFT) 21 (subcooled and two-phase flow).

The experimental facility consisted of a large vessel 5.2 m in diameter and 22 m high having a total volume of 420 m³. A discharge pipe containing a valve, a nozzle, rupture discs and assorted transducers was attached to the bottom of the vessel. For JIT 11 a standpipe, 1 m in diameter and 18 m tall, was mounted within the vessel to prevent any liquid from entering the discharge pipe. The nozzle used for the saturated steam flow test (JIT 11) had a diameter of 0.3 m and a length of 1.18 m. The nozzle used for the subcooled critical flow test (CFT 21) had a 0.5 m diameter and was 0.96 m in length.

For all the RELAP5 simulations the experimentally measured fluid conditions in the vessel were used as boundary conditions. This technique allowed the simulations to focus on the flow in the discharge pipe.

The simulations of saturated steam flow overpredicted the experimental discharge flow rate by 20 to 25 percent. Explicitly representing the nozzle region by up to five computational cells had little effect on computed results. It was concluded that, when simulating saturated steam critical flow with RELAP5, a discharge coefficient of ~ 0.8 needs to be applied. Furthermore, short lengths of pipe ($L/D < 4$) at the discharge should not be explicitly modeled.

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Numerical discontinuities in calculated critical flow rate were found to occur in some of the saturated steam flow simulations. The cause of the discontinuities was traced to an approximation made in the equation used for determining the internal energy at a junction in subroutine JCHOKE.

When simulating CFT 21 RELAP5 was found to overpredict critical flow rates of subcooled liquid by 18 to 20 percent when the nozzle was not explicitly included in the RELAP5 model (only its flow area was included). Good agreement with experimental results was attained by using a discharge coefficient of 0.85.

When the nozzle was included in the RELAP5 model RELAP5 underpredicted the measured flow rates. Applying discharge coefficients greater than unity did little to improve computed results but greatly increased computational times. It was concluded that when modeling discharge regions using RELAP5 explicit representation of short lengths of piping near the discharge location should be avoided.

For low quality two phase flow RELAP5 was in good agreement with experimental data when the vessel fluid state (RELAP5 boundary condition) was based upon gamma densitometer measurements. When the fluid state was based upon dP measurements RELAP5 overpredicted the measured flow rate by up to 30 percent. Since the actual fluid state in the vessel probably lies between those used as boundary conditions it was concluded that RELAP5 would generally need a discharge coefficient of between 0.80 and 0.95 when used to simulate low quality critical flow.

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Application of a discharge coefficient to the RELAP5 simulation of low quality two-phase flow did not achieve an expected result. Using a discharge coefficient of 0.85 instead of 1.0 resulted in only a 8 percent reduction in flow rate rather than the 15 percent expected.

It was discovered that, because of the logic used in subroutine JCHOKE to select between the subcooled and saturated flow calculations and because of an apparent dependency of local equilibrium quality on discharge coefficient, the sonic velocities used in the RELAP5 choking criterion could increase when a discharge coefficient was applied, thus partially offsetting the velocity reduction represented by the discharge coefficient.

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1 INTRODUCTION

The International Thermal-Hydraulic Code Assessment and Applications Program (ICAP) is being conducted by several countries and coordinated by the USNRC. The goal of ICAP is to make quantitative statements regarding the accuracy of the current state-of-the-art thermal-hydraulic computer programs developed under the auspices of the USNRC.

Sweden's contributions to ICAP relate both to TRAC-PWR (1) and RELAP5 (2). The assessment calculations are being conducted by Studsvik Energiteknik AB for the Swedish Nuclear Power Inspectorate. The assessment matrix is shown in Table 1.

In this report the results of an assessment of the RELAP5's critical flow model is presented. The ability of RELAP5 to simulate the critical flow of saturated steam is assessed by comparison to data from Marviken Jet Impingement Test (JIT) number 11 (5). The subcooled critical flow model is assessed by comparison to data from Marviken Critical Flow Test (CFT) number 21 (6).

This report is organized as follows: Section 2 describes the experimental facility and section 3 describes the RELAP5 model used to simulate the experiments. In section 4 results from the simulations are presented and discussed. Computational efficiency of RELAP5 and numerical problems encountered during the simulations are given in section 5. Conclusions are presented in section 6.

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Table 1

ICAP Assessment Matrix - Sweden.

Code	Facility	Type		Description
		Sep. effect	Integral	
RELAP5	Marviken21	X		Subcooled Critical Flow
RELAP5	Marviken11	X		Critical Flow, level swell
RELAP5	FIX-II		X	Recirculation Line (10 %) break
RELAP5	FIX-II		X	Recirculation Line (31 %) break
RELAP5	FIX-II		X	Recirculation Line (200 %) break
RELAP5	LOFT		X	Cold Leg Break (4") pumps off
RELAP5	LOFT		X	Cold Leg Break (4") pumps on
RELAP5	FRIGG	X		Subcooled Void Distribution
RELAP5	FRICG	X		Critical Heat Flux
RELAP5	RIT	X		Post Dryout Heat Transfer
TRAC/PF1	Ringhals		X	Loss of Load

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2. FACILITY AND TEST DESCRIPTION

The Marviken Power plant was built as a boiling heavy water direct cycle nuclear reactor but was never commissioned. The nuclear steam supply system was left intact and an oil fired boiler was built to provide steam for the turbine.

During 1978 and 1979 Marviken was the site of the Critical Flow Test (CFT) program. This test program generated full scale critical flow data for subcooled liquid and low quality two-phase mixtures.

Subsequent to the CFT program, Marviken became the site of the Jet Impingement Test (JIT) program. This program, which focused on measuring loads due to a fluid jet impinging upon a flat plate, also generated full scale critical flow data. One of the tests, JIT 11, allowed only saturated steam to be discharged.

Figure 2-1 depicts the Marviken pressure vessel and the location of the differential pressure measurements. For JIT 11 a standpipe (dotted line) was inserted into the vessel to ensure that only steam flowed out of the vessel. In other tests no standpipe was used; the fluid entered the discharge pipe at the bottom of the vessel directly. The nozzle was located beneath the pressure vessel. The piping leading to the nozzle and the nozzle are depicted in Figures 2-2 and 2-3. Initial and boundary condition for JIT 11 and CFT 21 are summarized in Table 2-1. Complete descriptions of the experimental facility for the JIT program and for the CFT program are given in References 3 and 4 respectively. A description of JIT 11 is presented along with test results in Reference 5 and a description of CFT 21

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is given in Reference 6. The probable error (one standard deviation) in the measured differential pressure values shown in this report is 0.6 kPa; the 99 % confidence error is 1.5 kPa.

Table 2-1

Important parameters for Marviken JIT 11 and CFT 21

	JIT 11	CFT 21
Vessel volume (net internal)	420 m ³	420 m ³
Vessel inside diameter	5.22 m	5.22
Standpipe: height	18 m	-
outside diameter	1.04 m	-
wall thickness	8.8 mm	-
Discharge nozzle: diameter	0.299 m	0.500 m
area	702 x 10 ⁻⁴ m ²	0.1963 m ²
length	1.18 m	1.5 m
Initial pressure	5.0 MPa	4.9 MPa
Final pressure	1.88 MPa	2.5 MPa
Initial water level	10.2 m	19.9 m
Final water level	8.0 m	<0.8 m
Initial inventory: water	145 x 10 ³ kg	330 x 10 ³ kg
steam	5 x 10 ³ kg	6 x 10 ² kg
Maximum subcooling	< 3 K	33 K

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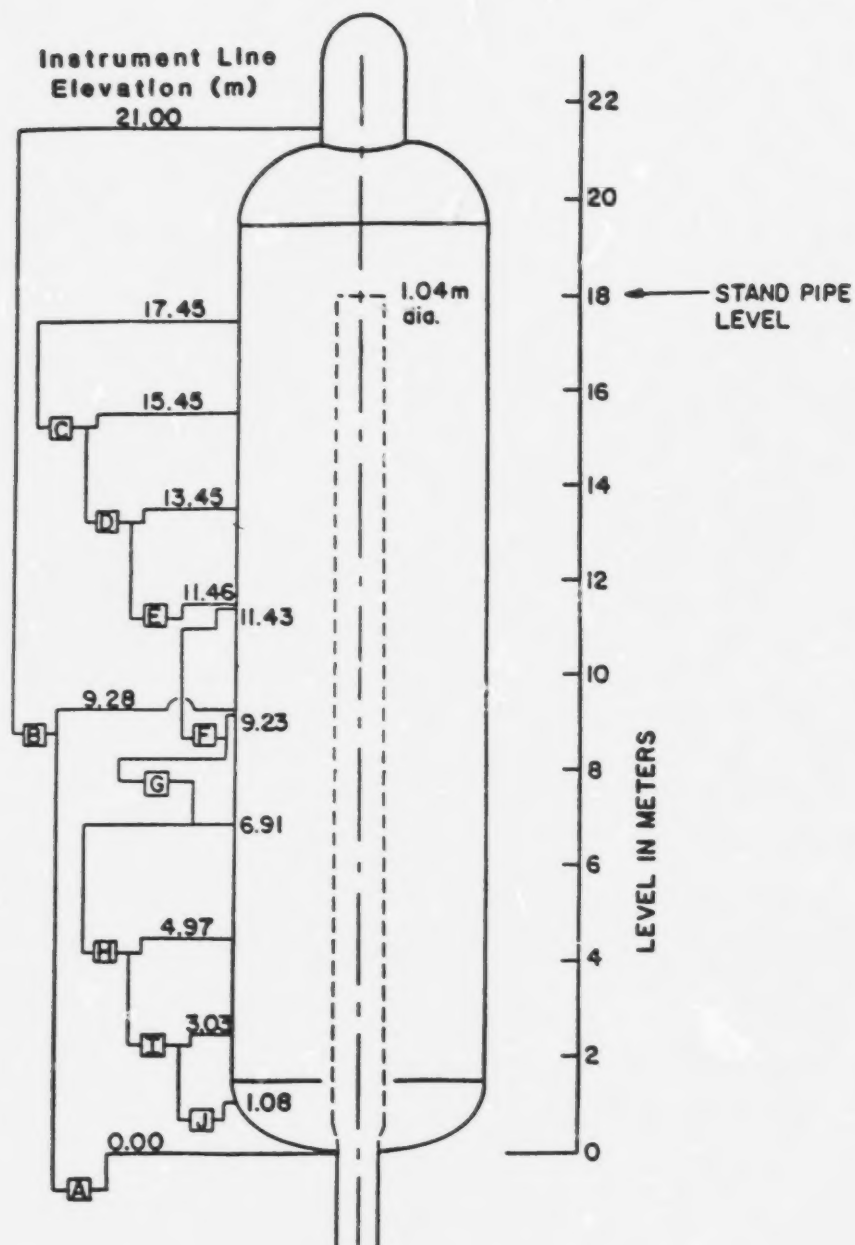


Figure 2-1

Marviken test vessel. Differential pressure transducers A through J.

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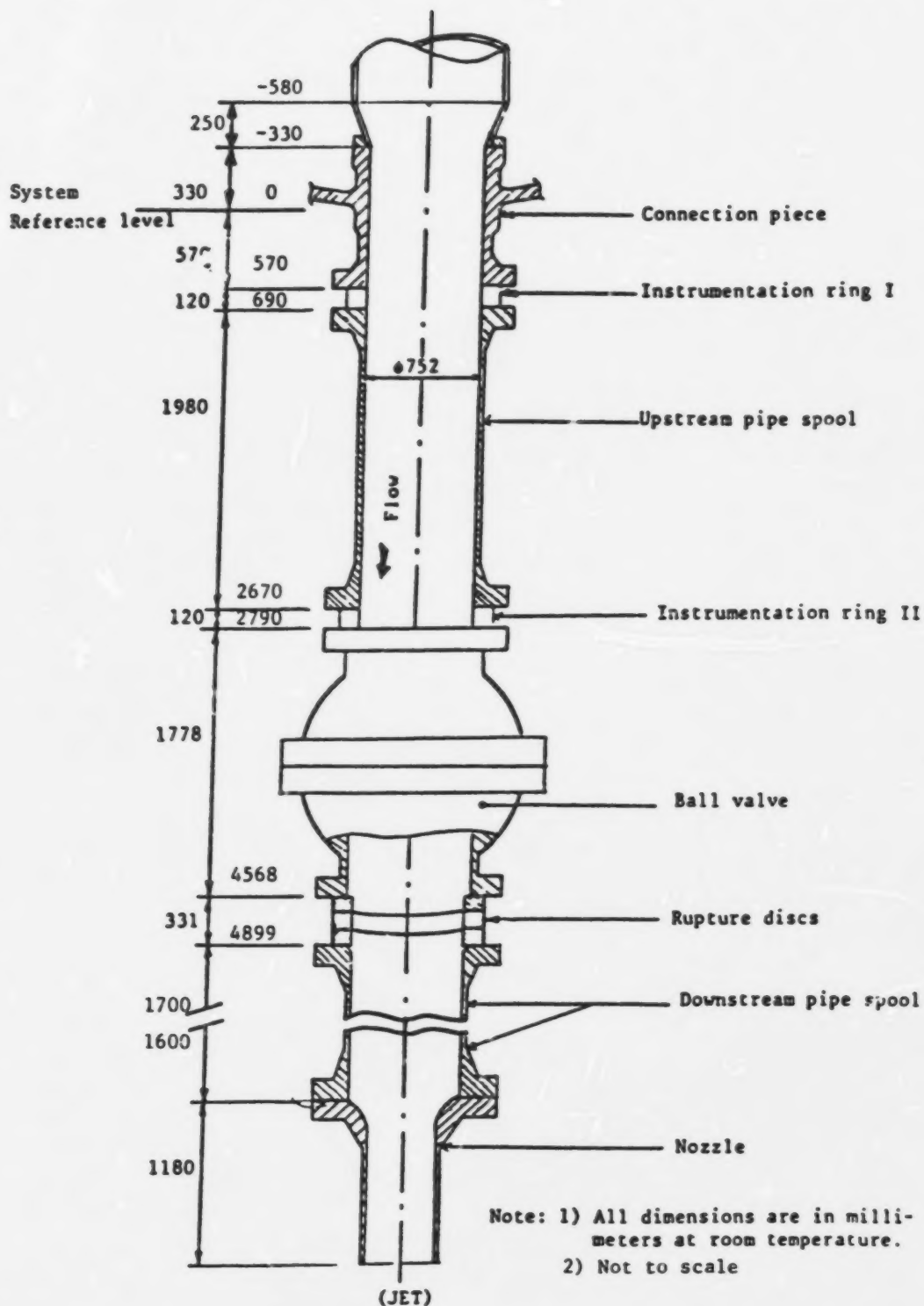


Figure 2-2

Arrangement of components in the discharge pipe
for Jet Impingement Test 11.

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Note: All dimensions are in millimeters at room temperature.

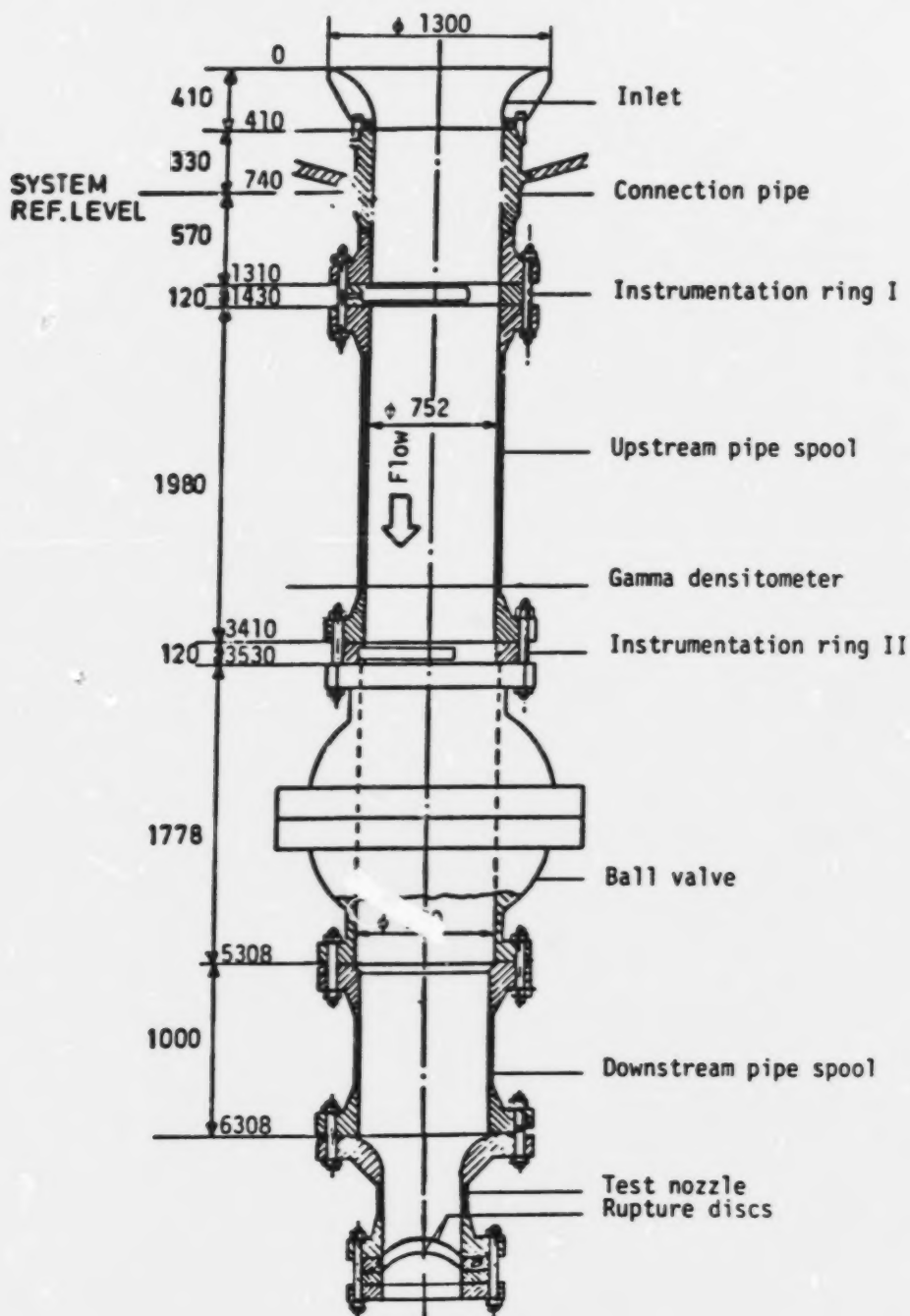


Figure 2-3

Arrangement of components in the discharge pipe for Critical Flow Test 21.

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3 CODE AND MODEL DESCRIPTION

The critical flow simulations of JIT 11 and CFT 21 were performed with RELAP5/MOD2, cycle 36.02.

3.1 Input description - JIT 11 simulations

In order to focus on the critical flow model in RELAP5 it was decided to drive RELAP5 with vessel boundary conditions determined from the experimental data. A TMDPVOL component was used to represent the vessel for all the simulations of JIT 11. The containment was also represented by a TMDPVOL component (with constant $P = 0.1$ MPa). The piping between the vessel and the containment (see Figures 2-1, 2-2) was represented several different ways, as described in Table 3-1.

Table 3-1

Description of the JIT 11 simulation cases

Case	Description
0 node	Vessel modeled as time dependent volume. Standpipe and discharge pipe not modeled. A single junction component used to represent the discharge area.
7 node	Vessel model as time dependent volume. Standpipe modeled as pipe component (4 cells). Discharge pipe modeled as pipe component (3 cells). Single junction component used to represent the discharge area.
9 node	Same as 7 node model except nozzle included. Nozzle modeled by pipe component (2 cells).
12 node	Same as 9 node model except nozzle now represented with 5 cells.

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3.2 Input description - CFT 21 simulations

For the simulations of CFT 21 a TMDPVOL component was used to represent the fluid conditions at the bottom of the vessel. For the simulations of sub-cooled flow the pressure and temperature measured at the vessel bottom were fed to RELAP5. For the simulations of saturated liquid or two-phase flow the pressure and fluid quality at the vessel bottom were fed to RELAP5. The fluid quality history was determined from experimental measurements of density, pressure, and differential pressure combined with the assumption of adiabatic flow between the vessel bottom and the gamma densitometer location (refer to Figure 2-3).

The RELAP5 simulations are described in Table 3-2. For simulations CFT01 to CFT06 the discharge pipe was modeled by a PIPE component with three cells. The discharge area was represented by a SNGLJUN component but the nozzle was not explicitly modeled. For simulations CFT07 and CFT08 the nozzle was modeled as a PIPE component having one cell.

The saturated flow simulations (CFT04, CFT05, CFT06) all began at 26.7 seconds into the blow-down. Each of these simulations was initiated by restarting case CFT03 and inputting a new (saturated conditions) set of boundary conditions representing the experimental measurements made between 26.7 and 60 seconds.

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Table 3-2

Description of the CFT 21 simulation cases.

RELAP5 case	Description
CFT01	Subcooled boundary conditions. No discharge coefficients. Nozzle not modeled.
CFT02	Subcooled boundary conditions. Subcooled discharge coefficient (C_D) = 0.85. Nozzle not modeled.
CFT03	Subcooled boundary conditions. C_D = 0.85. Boundary condition temperature reduced 2K for $t > 18$ s. Nozzle not modeled.
CFT04	Saturated boundary conditions. Restarted from CFT03 at 26.5 s. No discharge coefficient for two-phase flow.
CFT05	Saturated boundary conditions. Restarted from CFT03 at 26.5 s. No discharge coefficient. Bound- ary condition quality limited to upper value of 0.003.
CFT06	Same as CFT05 except C_D = 0.85.
CFT07	Subcooled boundary conditions. No discharge coefficient. Nozzle modeled with one node.
CFT08	Same as CFT07 except C_D = 1.09 for subcooled flow and 1.13 for two-phase flow.

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4 RESULTS AND DISCUSSION

RELAP5 simulations of the critical flow of saturated steam (JIT 11) are reported in section 4.1. Simulations of the subcooled critical flow and the low quality two-phase critical flow of CFT 21 are discussed in sections 4.2 and 4.3, respectively.

4.1 Critical flow of saturated steam - JIT 11

For the RELAP5 simulation of the critical flow in JIT 11 the experimentally measured pressure in the vessel was used as a boundary condition. Calculated discharge flow rate was then compared to the measured flow rate. The pressure history and the discharge mass flow rate history for JIT 11 are given in Figures 4-1 and 4-2.

The results of all the RELAP5 simulations of JIT 11 are shown together with the experimental data in Figure 4-3. Error bounds on the measured mass flow rate are also indicated.

Regardless of the nodalization used, RELAP5 overpredicted the discharge flow rate. Except for anomalous flow increases in the 0 node, and 9 node cases, the 0 node, 7 node, and 9 node cases yielded nearly the same flow rate. The 12 node calculation yielded a slightly better prediction of the measured flow rate.

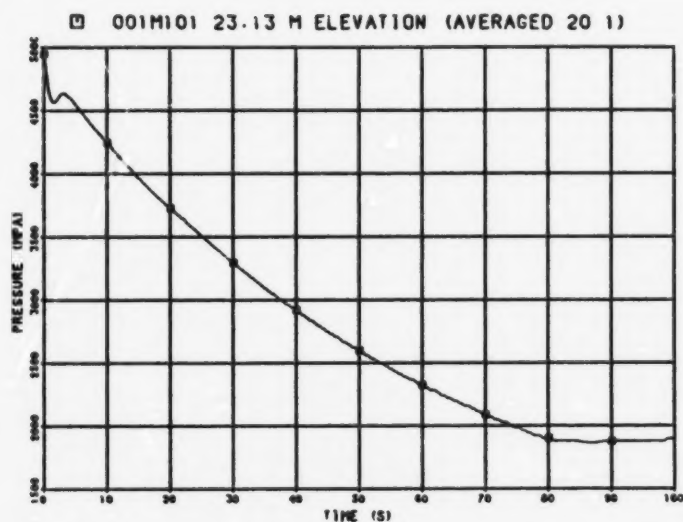
The anomalous (and incorrect) increases in flow rate for the 0 node and the 7 node cases have been traced to an approximation made in the calculation of the internal energy at a junction experiencing choked flow. This is discussed further in section 5.

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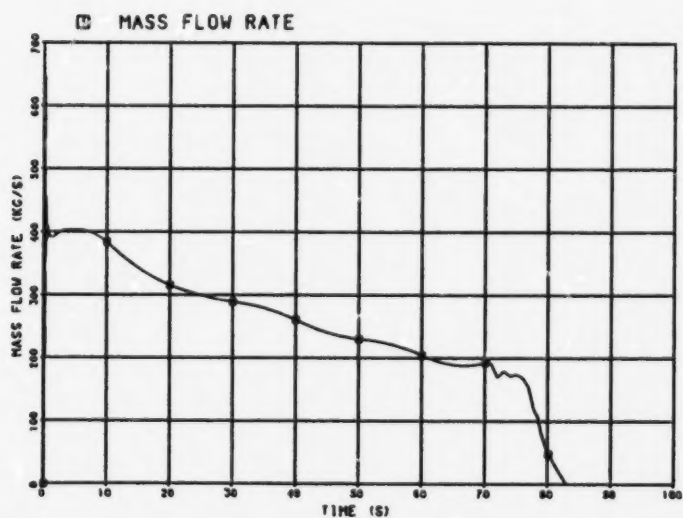
Figure 4-3 indicates that there is little incentive to nodalize discharge piping extensively in RELAP5. Computational costs rise rapidly as nodes are added in the nozzle region (due to the material Courant limit on time step size) yet little improvement is obtained in computed results.

The computed results shown in Figure 4-3 can be brought into fairly good agreement with the experimental results by application of a 0.83 multiplier. This suggests that when using RELAP5 for calculating the discharge of saturated steam through a nozzle having a well rounded entrance, a discharge coefficient of 0.83 should be applied.

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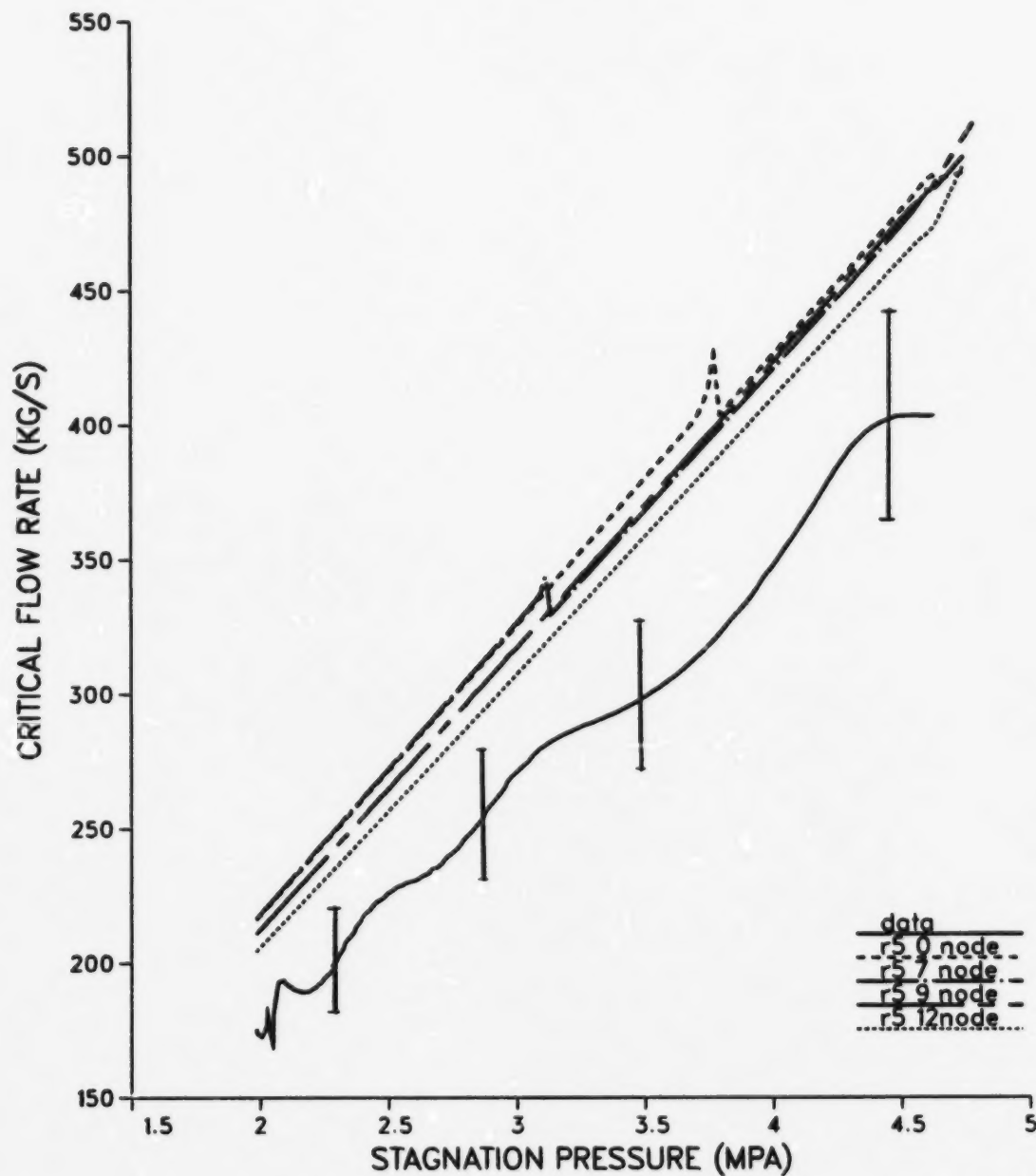
Figure 4-1

Measured vessel pressure for Marviken JIT 11.
RELAP5 boundary condition.

Figure 4-2

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CRITICAL FLOW — MARVIKEN JIT 11

**Figure 4-3**

Critical flow of saturated steam.
RELAP5 simulations and JIT 11 data.

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4.2 Subcooled critical flow - CFT 21

The subcooled critical flow model in RELAP5 was assessed against Marviken experiment CFT 21 by driving a RELAP5 model of the discharge piping with boundary conditions (pressure and temperature) measured near the inlet to the discharge piping. Calculated values of discharge flow rate, pressure drop across the discharge pipe inlet, and fluid quality in the discharge pipe were compared to measured values.

In CFT 21 the subcooled blowdown lasted for the first 25-30 seconds of the 60 second test period.

The pressure boundary condition used in RELAP5 was taken from pressure transducer 001M106 (Figure 4-4). The temperature boundary condition was taken as the average reading from thermocouples 001M521 and 001M402. These thermocouples are located at the 0.74 m elevation and 0.75 m from the vessel axis. The amount of subcooling (saturation temperature minus liquid temperature) in the boundary conditions is shown in Figure 4-5.

Figure 4-6 compares the RELAP5 base case (CFT01) calculated discharge flow rate history to the measured one. RELAP5 overpredicted the discharge flow rate. The gradual decline in the measured flow rate beginning at 22 s is associated with vapour formation in the discharge piping. Figure 4-7 shows the experimentally determined fluid quality in the discharge pipe based upon a gamma densitometer measurement. RELAP5 calculated only a brief period of two-phase flow in the discharge pipe. The calculated flow rate dropped sharply when bubbles were calculated to exist.

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In Figure 4-8 the differential pressure from the discharge pipe to the vessel interior is shown. The calculated pressure loss across the discharge pipe inlet agrees well with the measured pressure loss. It is slightly larger than the measured loss but this may be the result of calculated velocities in the discharge pipe being higher than measured ones. The good agreement between calculated and measured pressure loss rules out pressure discrepancies in the discharge pipe as a cause of the flow rate discrepancies seen in Figure 4-6.

Rerunning the RELAP5 calculation and using a discharge coefficient of 0.85 (case CFT02) brought the calculated and measured flow rates into agreement for the first 22 seconds of the transient (Figure 4-9). For this RELAP5 calculation the pressure loss across the discharge pipe inlet was slightly less than the measured loss (Figure 4-10). The difference between the calculated and measured loss is probably due to no form loss coefficient being used in the RELAP5 model. A form loss coefficient of 0.15, if used in the RELAP5 model, would bring the calculated pressure loss into very good agreement with the measured loss.

The inability of RELAP5 to calculate the decline in flow rate after 22 s is due to the fact that RELAP5 calculated essentially no vapour formation in the discharge pipe. The experimental data indicate vapour formation beginning at 22 s.

One possible reason for the discrepancy between calculated and measured flow rates after 22 s is that the fluid temperature boundary condition used in RELAP5 is not a true measure of the tem-

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perature at the entrance to the discharge piping. The thermocouples whence the boundary condition is taken are 0.75 m from the vessel central axis. Moreover a radial temperature distribution did exist during the experiment (6).

In order to test the hypothesis that the RELAP5 overprediction of flow rate after 22 seconds was partly due to uncertainty in the boundary temperature, a RELAP5 simulation (case CFT03) was conducted in which the boundary fluid temperature was reduced 2K for $t > 18s$ (the discharge coefficient was left at a value of 0.85). Two degrees Kelvin corresponds to the maximum error associated with the temperature measurements (the 1 σ error is 0.6K) and is believed to be encompass the probable radial temperature variation.

The good agreement between calculated and measured flow rates (Figure 4-11) which resulted when the boundary temperature was changed proved the hypothesis. The calculation ended at 26.7s when the boundary condition subcooling vanished.

4.2.1 Nodalization study

In the RELAP5 simulations discussed thus far the nozzle was not included in the model and a discharge coefficient of 0.85 was required to bring the calculated flow rate into agreement with the experimental flow rate. To explore the sensitivity of calculated results to nodalization a RELAP5 simulation (case CFT07) was performed in which the nozzle was modelled by one computational cell. It was thought that this simulation might yield computed flow rates which agreed with experimental ones without using any discharge coefficient. Choking was allowed only at the nozzle outlet for this simulation.

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The results of the one-node-nozzle simulation are depicted in Figures 4-12 and 4-13.

The discharge mass flow was underpredicted by RELAP5 and the pressure in the nozzle was overpredicted. From these results one concludes that, if a complete description of the experimental geometry is included in the RELAP5 model a discharge coefficient greater than 1.0 is required to bring computed flow rates into agreement with measured ones.

The one-node-nozzle simulation was rerun (case CFT 08) using values of 1.09 and 1.13 for the subcooled and saturated critical flow coefficients. This simulation did not improve calculated discharge flow rate (Figure 4-14). The computed flow rate exhibited erratic behaviour generally associated with numerical problems and, indeed, this RELAP5 simulation was very inefficient, taking 2 947 time steps and repeating 1 416 time steps for the 30s transient. When no discharge coefficients were used the simulation required only 1 242 time steps and repeated 620.

4.3 Low quality critical flow - CFT 21

In order to study the RELAP5 critical flow model's response to low quality two phase flow the subcooled flow simulation which gave the best agreement with experimental data (case CFT 03) was restarted (at 26.7 s) and saturated boundary conditions were imposed at the discharge pipe inlet. The boundary condition pressure was taken from pressure transducer 001M106. The boundary condition fluid quality was calculated (5) based upon the gamma densitometer reading and the assumption of an adiabatic fluid expansion

between the vessel bottom and the location of the densitometer in the discharge pipe. The boundary conditions as depicted in Figure 4-16 and 4-17.

The flow rate history from the saturated boundary condition base simulation (case CFT 04) is shown together with the measured flow rate in Figure 4-18. For completeness, the subcooled portion of the transient (case CFT 03) has also been included. The computed and measured mass flow rates agree well with one another. These results imply that RELAP needs no discharge coefficient when simulating low quality two phase critical flow through large pipes.

Subsequent to the CFT 04 simulation it was discovered that the experimental data offered conflicting indications of what the boundary condition fluid quality was during the 30 to 60 s time range. While the gamma densitometer indicated a fluid quality history as shown in Figure 4-17, the differential pressure measurement 007M246 indicated that the fluid quality never rose beyond 0.003. Thus, the rapid increase in quality occurring around 40 s may not have been real.

To explore the effect which the uncertainty in the boundary condition quality had upon computed results, the RELAP5 CFT 04 simulation was rerun with the boundary condition quality limited to a value of 0.003 (case CFT 05). This change only affected the condition for $t > 35$ seconds.

The flow rate calculated by case CFT 05 was higher than the measured flow rate (Fig 4-19). The results suggested that a two-phase discharge coefficient value similar to that used for the subcooled blow-

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down might be applicable. For $t > 40$ s the average value of the ratio of measured to calculated flow rate is 0.85.

RELAP5 simulation CFT 06 was a rerun of CFT 05 but utilized a two phase flow discharge coefficient of 0.85. It was thought that CFT 06 would give a flow rate which was in much better (relative to CFT 05) agreement with the experimental data. In fact, this was not the case, as can be seen by comparing Figures 4-19 and 4-20. In spite of applying a discharge coefficient which should have reduced the calculated flow rate so that it fell upon or below the experimental data, the calculated flow rate remained greater than the measured flow rate. This result implied a feedback existed between the flow solution and the discharge coefficient - an unexpected feedback.

Having feedback between a critical flow discharge coefficient and the flow solution is undesirable because one wants to use discharge coefficients as free parameters - ones which can be used to reduce the discharge flow by a predictable amount.

In order to explain the feedback between the discharge coefficient and the flow solution a degression - a brief review of the mechanics of choking in RELAP5 - is needed.

The RELAP choking criterion is (Eq 333 of Ref 2)

$$\frac{\alpha_f \rho_f V_f + \alpha_g \rho_g V_g}{\alpha_f \rho_f + \alpha_g \rho_g} = C_D a_{HE} \quad (\text{Eq 4-1})$$

The discharge coefficient, C_D , is the two phase discharge coefficient (input by the user) whenever the void fraction, α_g , is greater than 0.02. Otherwise C_D is the subcooled discharge coefficient.

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For subcooled choking the quantity a_{HE} is the maximum of the local homogeneous equilibrium (HE) sound speed and a speed calculated by applying Bernoulli's flow equation together with the Alamer-Lienhard-Jones correlation.

Detailed examination of the RELAP5 simulations CFT 05 and CFT 06 showed that the sonic velocity being used for subcooled flow calculations in JCHOKER was generally six to eight percent greater than that used for saturated calculations in JCHOKER.

Two-phase choking is applied if choking is indicated and the local void fraction is greater than 10^{-7} and the local equilibrium quality is greater than 2.5×10^{-4} . If these criteria are not met then single phase liquid choking is applied.

Underrelaxation is applied to the choked flow model velocities as long as the local equilibrium quality is less than 2.5×10^{-3} and the local void fraction is greater than 10^{-7} . For the cases being considered the underrelaxation was always applied. The underrelaxation algorithm ($v^{n+1} = 0.9 v^n + 0.1 v^{n+1}$) is heavily weighted to old time values. Thus, once a junction velocity is established a large change in velocity resulting from the solution of Eq 4-1 will not show up in the choked junction velocity unless the change persists for several time steps.

With the above points in mind one can return to the RELAP5 cases. The discharge junction velocities and void fractions from the RELAP5 simulations are illustrated in Figures 4-21 and 4-22. The discharge velocity was the same for cases CFT 04 and CFT 05 but the discharge void fraction was much larger after 40 s in case CFT 04. Thus the difference in discharge flow rate between

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case CFT04 and CFT05 can be attributed to a changing void fraction. On the other hand, the discharge void fraction was nearly the same for cases CFT05 and CFT06 but the discharge velocity was lower - but not 15 percent lower in case CFT06.

The reason the application of $C_D = 0.85$ did not reduce the discharge velocity by 15 % is contained in Figures 4-23 and 4-24. These figures illustrate the fluid equilibrium quality at the discharge junction. For completeness the static quality has also been plotted. Recall that the equilibrium quality value determines whether the saturated or subcooled critical flow model is active.

Comparing Figure 4-23 to Figure 4-24 one sees that when the discharge coefficient was applied, the equilibrium quality at the discharge junction was depressed - on the average, it remained less than 2.5×10^{-4} more time than it did when no discharge coefficient was used. Thus the choked flow velocities coming from the subcooled critical flow model played a stronger role (because of the under-relaxation algorithm, the model, subcooled or two phase, which is selected for most of the time steps dominates the calculation of the local junction velocity) in CFT06 compared to CFT05.

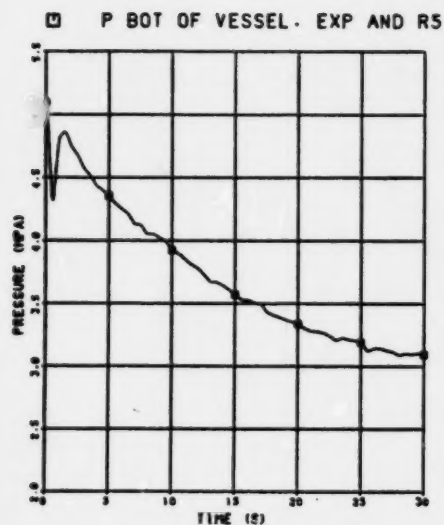
Because sonic velocities (a_{HE} in Eq 4-1) used in the subcooled critical flow logic were six to eight percent greater than those in the two-phase critical flow logic the longer time which case CFT 06 spent in the subcooled flow logic led to a value of a_{HE} which was greater than that seen in CFT 05, enough greater to offset half of the 15 % reduction represented by the discharge coefficient.

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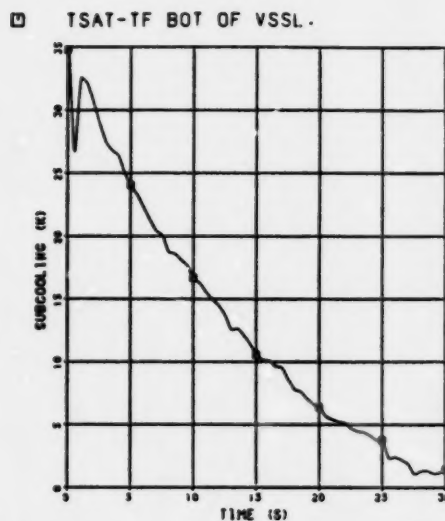
The above analysis has revealed why application of a discharge coefficient may not reduce computed flow rates in a predictable manner during low quality flow simulations. The next question to address is how the situation might be rectified.

The undesirable feedback could be eliminated by introducing logic into subroutine JCHOK to ensure that the velocity a_{HE} used in the RELAP5 choking criterion is continuous at the interface between the subcooled choking model and the two-phase flow choking model.

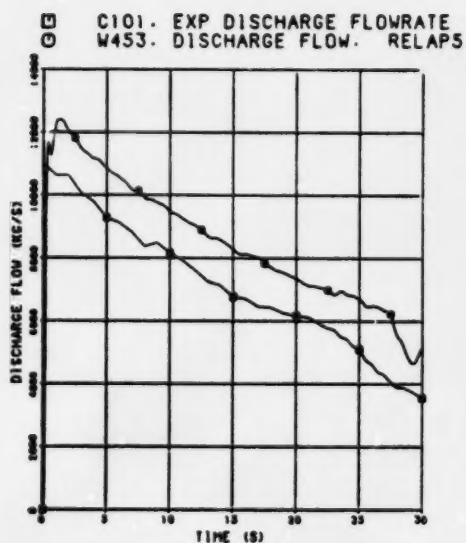
The feedback could also probably be eliminated by eliminating the erratic behavior of the equilibrium quality evident in Figures 4-21 and 4-22 or else having the critical flow model selection logic depend more upon static rather than equilibrium quality. Since the erratic behaviour of the equilibrium quality is undoubtedly of numerical origin, it would appear to be a likely candidate for improvement.

**Figure 4-4**

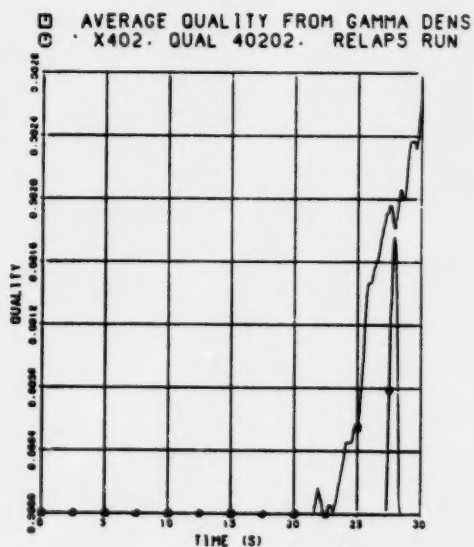
Pressure Boundary Condition for Case CFT 01.

**Figure 4-5**

Subcooling Boundary Condition for Case CFT 01.

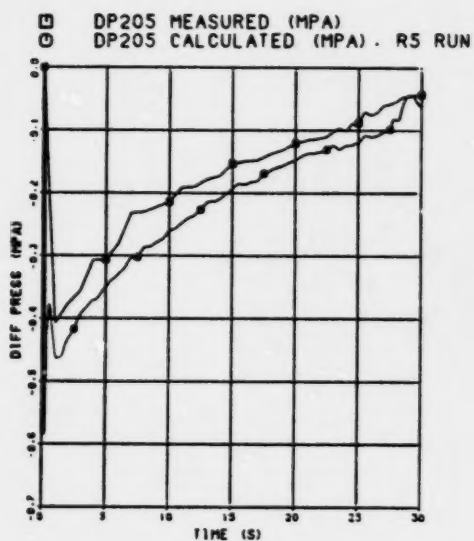
**Figure 4-6**

Discharge Flow Rate. Measured and Case CFT 01.

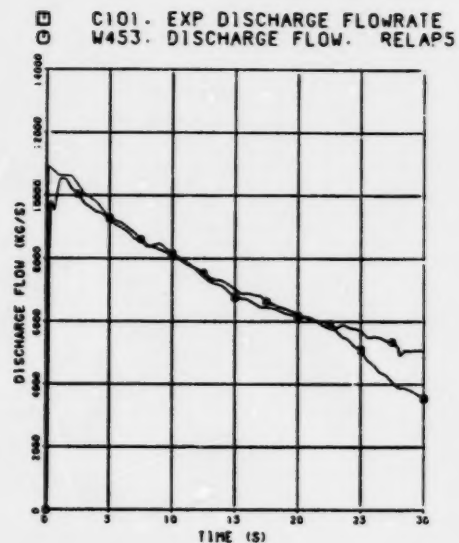
**Figure 4-7**

Fluid Quality in the Discharge Pipe.

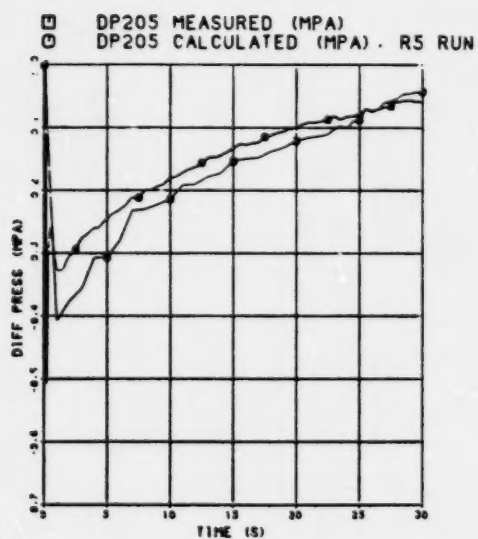
1986-07-25

**Figure 4-8**

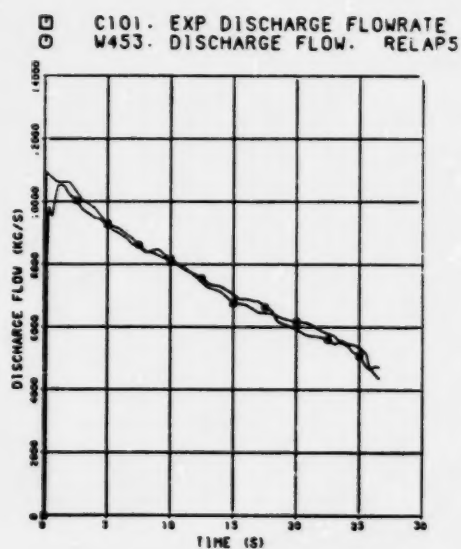
dP Across the Vessel Outlet. Measured and Case CFT 01.

**Figure 4-9**

Discharge Flow Rate. Measured and Case CFT 02.

**Figure 4-10**

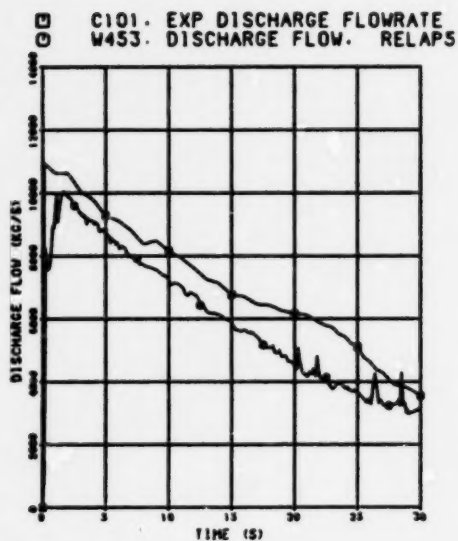
dP Across the Vessel Outlet. Measured and Case CFT 02.

**Figure 4-11**

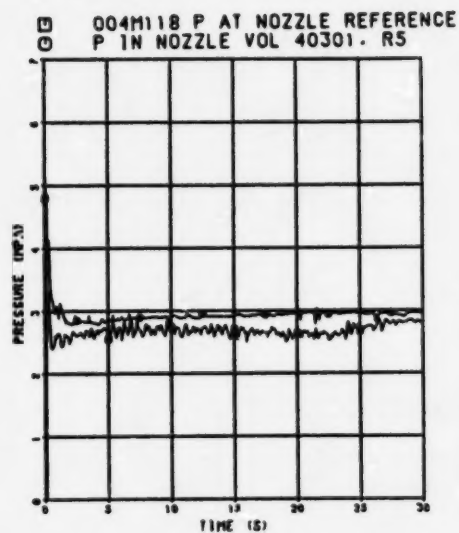
Discharge Flow Rate. Measured and Case CFT 03.

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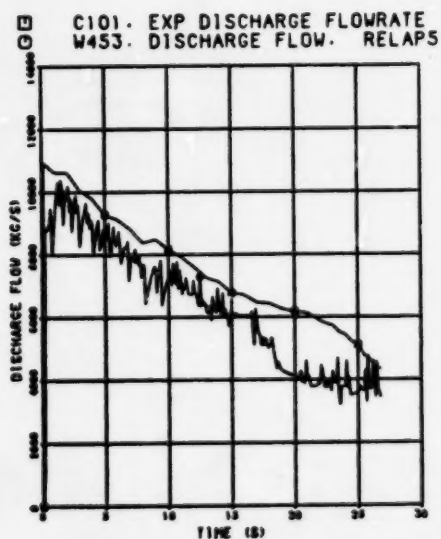
1986-07-25

Figure 4-12

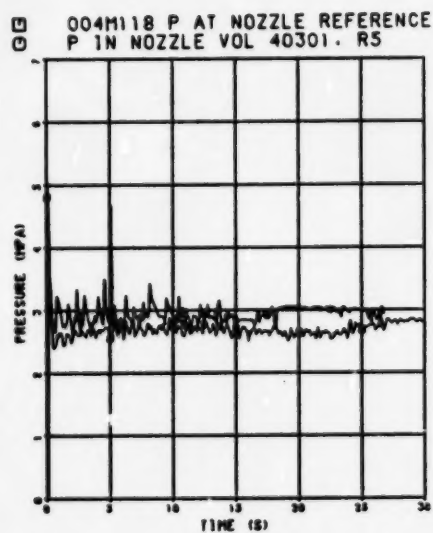
Measured and Calculated (Case CFT 07) Discharge Flow Rate.

Figure 4-13

Measured and Calculated (CFT 07) Pressure in the Nozzle.

Figure 4-14

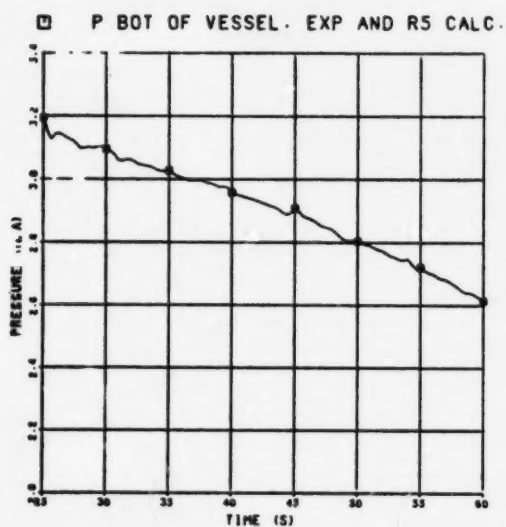
Measured and Calculated (CFT 08) Discharge Flow Rate.

Figure 4-15

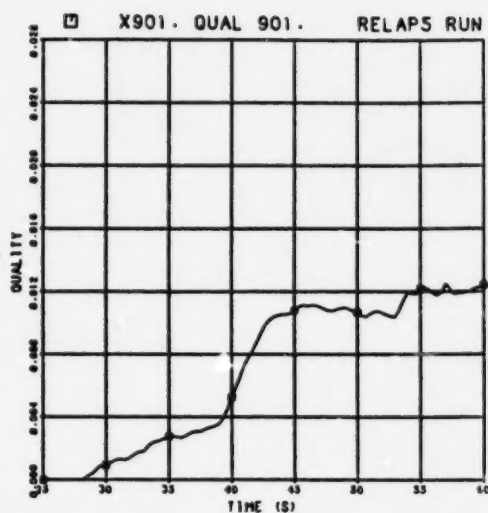
Measured and Calculated (CFT 08) Pressure in the Nozzle.

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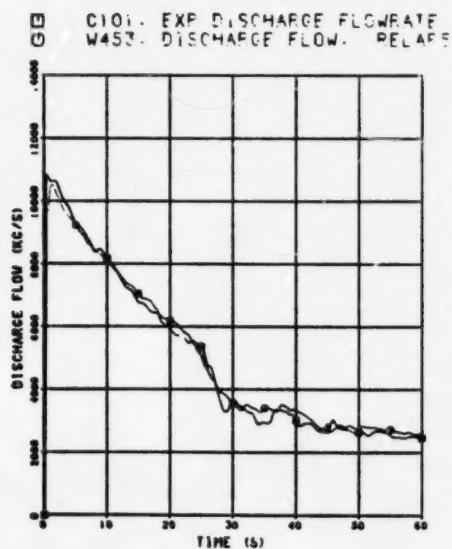
1986-07-25

**Figure 4-16**

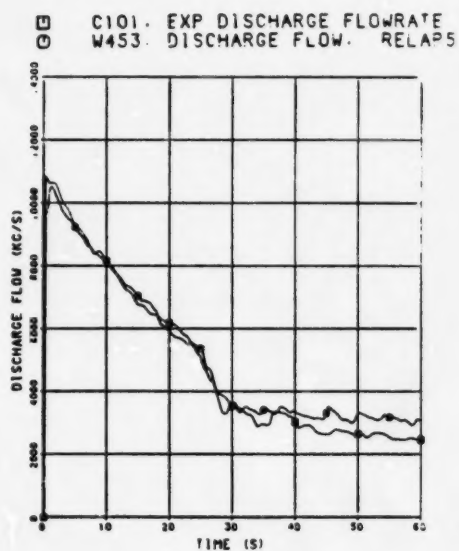
Pressure Boundary Condition of Saturated Flow Simulations.

**Figure 4-17**

Fluid Quality Boundary Condition for Saturated Flow simulations.

**Figure 4-18**

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 04).

**Figure 4-19**

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 05).

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Q C101. EXP DISCHARGE FLOWRATE
 Q M453. DISCHARGE FLOW. RELAP5 RUN

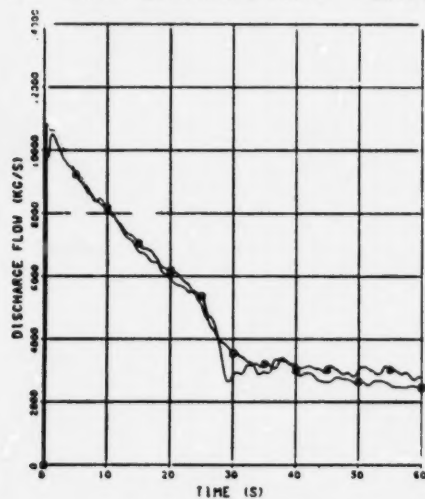


Figure 4-20

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 06).

Q VF04. L10. VELOCITY J453 (CFT04)
 Q VF05. L10. VELOCITY J453 (CFT05)
 Q VF06. L10. VELOCITY J453 (CFT06)

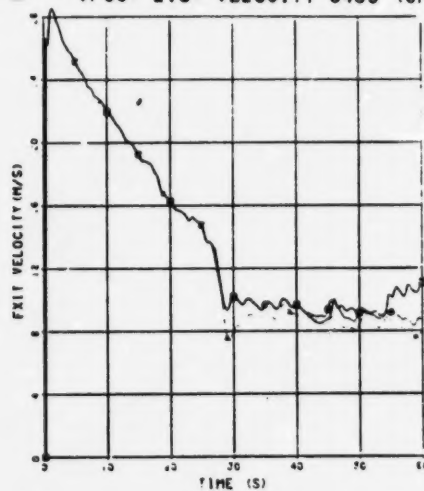


Figure 4-21

Liquid Velocity at the Discharge Junction. RELAP5 Cases CFT 04, CFT 05 and CFT 06.

Q A004. EXIT VOID FRACTION (CFT04)
 Q A005. EXIT VOID FRACTION (CFT05)
 Q A006. EXIT VOID FRACTION (CFT06)

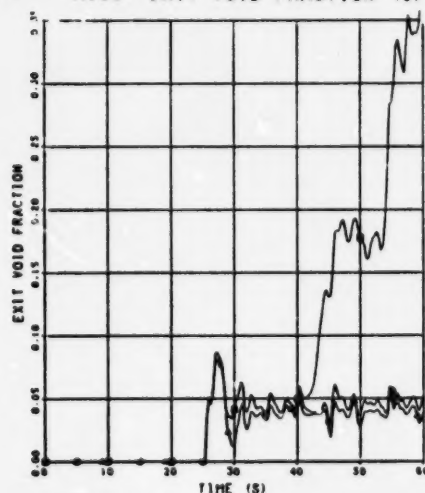


Figure 4-22

Void Fraction at the Discharge Junction. RELAP5 Cases CFT 04, CFT 05 and CFT 06.

Q XS03. QUALS 40203.
 Q XE03. QUALE 40203.

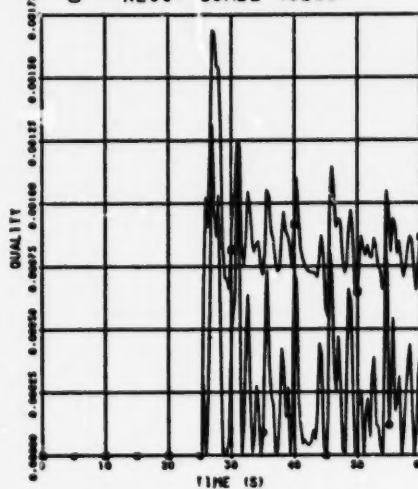


Figure 4-23

Static and Equilibrium Quality at the Discharge Junction. Case CFT 05.

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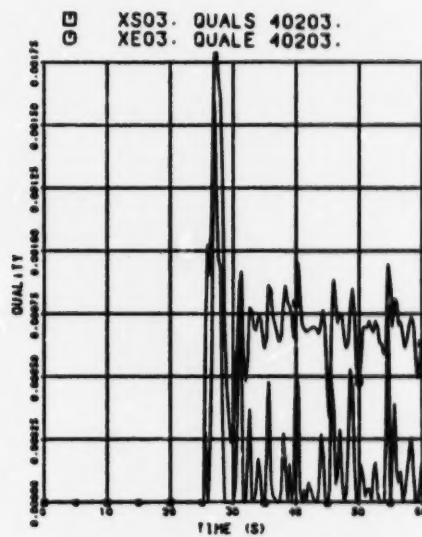


Figure 4-24

Static and Equilibrium Quality at the Discharge Junction. Case CFT 06.

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5 COMPUTATIONAL EFFICIENCY AND NUMERICAL PROBLEMS

The computational efficiency of the RELAP5 simulations are summarized in Tables 5-1 and 5-2. The simulations were conducted on a CYBER 180-810 computer.

The simulations of JIT 11 were limited by the material Courant limit except for the case in which the standpipe and discharge pipe were not included in the model. Simulation times increased dramatically when the nozzle was introduced into the model (9 mode and 12 mode simulations). Considering the similarity of computed results amongst the various simulations it is apparent that including the nozzle in the RELAP5 model was not cost effective.

The simulations of CFT 21 proceeded at the maximum allowed time step size when the saturated portion of the test was being simulated (CFT 04, CFT 05, CFT 06). For the simulations of the sub-cooled portion of the test the time step size was restricted to 0.05 s for the first 15 s due to the material Courant limit. Simulations CFT 07 and CFT 08 in which the nozzle was modeled proceeded quite slowly and had to repeat a large number (about 50 % of the total shown in the table) of time steps.

Table 5-1

Run Statistic For The JIT 11 Simulations.

Case	DT Max	Actual time steps	CPU (s)	CPU/Cell/ Step
0 Node	0.001 (t < 0.01)	808	43.	0.05
	0.01 (0.01 < t < 0.5)			
	0.10 (0.5 < t < 75.)			
7 Node	0.001 (t < 0.01)	1 552	296.	0.03
	0.01 (0.01 < t < 0.5)			
	0.10 (0.5 < t < 75.)			
9 Node	0.001 (t < 0.01)	60 002	13 995.	0.03
	0.01 (t > 0.01)			
12 Node	0.001 (t < 0.01)	239 969	70 481.	0.02
	0.01 (t > 0.01)			

Table 5-2

Run Statistics for the CFT 21 Simulations.

Case	Transient	DT Max	Actual time steps	CPU (s)	CPU/Cell/ Step
CFT01	0 - 30 s	0.1	481	60.	0.04
CFT02	0 - 30 s	0.1	419	47.	0.04
CFT03	0 - 26.7 s	0.1	386	42.	0.04
CFT04	26.7 - 60 s	0.1	334	36.	0.04
CFT05	26.7 - 60 s	0.1	334	37.	0.04
CFT06	26.7 - 60 s	0.1	334	37.	0.04
CFT07	0 - 30 s	0.1	1 242	211.	0.06
CFT08	0 - 30 s	0.1	2 947	484.	0.05

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5.1 Critical Flow Model numerical problems

Two of the RELAP5 simulations of JIT11 exhibited nonphysical jumps (see Figure 4-1). An investigation showed that the jumps occurred because the thermodynamic state at the discharge junction was calculated to switch from two phase to single phase vapor. Physically the junction should have remained in a two-phase state throughout the transient.

It was discovered that the erroneous thermodynamic state was calculated because of the approximation being used to find the internal energy at a choked junction (subroutine JCHOKE).

Assuming a quasi-steady, adiabatic flow, the internal energy at a junction may be calculated from (j = junction; up = upstream):

$$e_j = e_{up} + \frac{P_{up}}{\rho_{up}} - \frac{P_j}{\rho_j} - \frac{v_{up}^2 - v_j^2}{2}$$

In RELAP5, the term P_j/ρ_j is replaced by P_j/ρ_{up} . This approximation can result in an e_j value corresponding to vapor when the true value would correspond to two-phase. Because the sound speed (determined from (P_j, e_j)) is discontinuous at the two phase/vapor interface a jump in the calculated choked flow velocity occurs when the approximation for P_j/ρ_j leads to an incorrect value of e_j .

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6

CONCLUSIONS

1. RELAP5 critical flow model overpredicts the critical flow of saturated steam. For the JIT 11 simulations the calculated critical flow could be brought into agreement with the measured flow by applying a discharge coefficient of 0.82.
2. Computed results for JIT 11 were not substantially improved by modeling the nozzle. Considering the empirical nature of the RELAP5 choked flow model it is concluded that there is no benefit in modeling discharge piping having $L/D < 4$ when steam is being discharged.
3. An approximation made in the calculation of junction internal energy in subroutine JCHOKE is responsible for nonphysical jumps in computed discharge mass flow rate evident in two of the JIT 11 simulations.
4. RELAP5 overpredicted the subcooled critical mass flow rate for CFT 21 when the nozzle was not explicitly modeled. Calculated mass flow rates could be made to agree with measured ones by using a discharge coefficient of 0.85 in RELAP5.
5. When the nozzle geometry was explicitly modeled in RELAP5 mass flow rates for CFT 21 were underpredicted. Application of discharge coefficients (greater than unity) did not improve computed results; on the contrary, doing so gave rise to a very numerically noisy solution. It is concluded that short discharge nozzles or pipes ($L/D < 2$) should not be modeled explicitly in RELAP5.

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6. For the saturated blowdown portion of CFT 21 RELAP5 simulated the discharge flow quite accurately when the bounding condition fluid quality was based upon the gamma densitometer measurement. No discharge coefficient was needed to achieve agreement with the experimental data.
7. When the fluid quality boundary condition was lowered (based upon vessel differential pressure measurements) RELAP5 overpredicted the discharge flow rate.
8. The RELAP5 simulation of the discharge of low quality two-phase fluid did not respond in a predictable manner when discharge coefficients were applied. It was determined that a feedback exists for low quality flow such that application of a discharge coefficient may increase the value of the sonic velocity used in the choking criterion (Eq 4-1) partially offsetting the sonic velocity reduction represented by the discharge coefficient. Application of a discharge coefficient of say, 0.85, will reduce computed flow by only 7 or 8 percent instead of the 15 percent one might expect.

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5. The Marviken Full Scale Jet Impingement
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6. The Marviken Full Scale Critical Flow
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September 1979.
7. The Marviken Full Scale Critical Flow
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APPENDIX A

INPUT FOR RELAPS FOR JIT 11 SIMULATION

* CRITICAL FLOW TEST MARVIKEN TEST 11

* HIGH QUALITY STEAM.

*

* INPUT PREPARED BY ASTEN ROSDAHL

*

STUDSVIK ENERGITEKNIK AB, SWEDEN

*

*

0000100 NEW STDY-ST

0000101 RUN

0000102 SI SI

0000105 30. 40.

*

	REF VOL	LEVEL	FLUID	
0000120	200010000	18.33	WATER	MARVIKEN

*

***** TIME STEP CONTROL CARDS

	END-TIME	DTMIN	DTMAX	OPT	MINOR	MAJOR	RESTART
0000201	0.01	1.0-6	.001	00003	1	100	200
0000202	0.5	1.0-6	.01	00003	5	100	200
*0000203	10.0	1.0-6	.01	00003	50	1000	1000
*0000204	75.0	1.0-6	.01	00003	50	1000	1000
0000203	10.0	1.0-6	.1	00003	50	1000	1000

*

***** MINOR EDIT REQUESTS

301 MFLOWJ 450000000

302 MFLOWJ 451000000

303 MFLOWJ 452000000

304 MFLOWJ 453000000

*

***** TRIP INPUT DATA

0000501 TIME 0 GT NULL 0 10000.0 L *

*

*

*

***** HYDRAULIC COMPONENTS

*

=====

2000000	VESSEL	SNGLVOL	* 18.330 TO 18.830
4010000	STPIPE	PIPE	* 18.330 TO 0.330
4020000	DCPIPE	PIPE	* 0.330 TO -7.599
4030000	NOZZLE	PIPE	* -7.599 TO -8.779
9010000	P-CONST	TMDPVOL	
9020000	ATMOS	TMDPVOL	

*

*

***** JUNCTIONS

*

2510000	VESSFILL	SNGLJUN
4500000	STAND-IN	SNGLJUN
4510000	DISCH-IN	SNGLJUN

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4520000 NOZZ-IN SNGLJUN
 4530000 NOZZ-OUT VALVE

***** COMPONENT INFORMATION CARDS

4010001 4
 4020001 3
 4030001 2

***** SNGLVOL, BRANCH AND TMDPVOL GEOMETRY CARDS

	AREA	LENGTH	VOLUME	HA	VANG	ELEVCH	ROUGH	DIAH	FE
2000101	0.	0.5	10.79	0.	90.	0.5	0.	.0	00
9010101	20.	1.	0.	0.	-90.	.000	20.-6	.0	00
9020101	0.	1.	1.	0.	-90.	.000	20.-6	.0	00

***** PIPE AND ANNULUS GEOMETRY CARDS

	VOLAREA	NR	
4010101	0.7854	4	* D = 1.000
4020101	0.4441	3	* D = 0.752
4030101	0.07022	2	* D = 0.299

	LENGTH	NR	
4010301	4.5	4	* 18.000/4
4020301	2.643	3	* 7.929/3
4030301	0.59	2	* 1.180/2

	VOLUME	NR
4010401	0.00000	4
4020401	0.00000	3
4030401	0.00000	2

	VANG	NR
4010601	-90.	4
4020601	-90.	3
4030601	-90.	2

	ROUGH	DIAH	NR
4010801	20.E-6	0.0	4
4020801	20.E-6	0.0	3
4030801	20.E-6	0.0	2

*** PIPE JUNCTION LOSS COEFFICIENTS

	FORWARD	REVERSE	NR
4010901	0.00	0.00	3
4020901	0.00	0.00	2
4030901	0.00	0.00	1

	FE	NR
4011001	00	4
4021001	00	3
4031001	00	2

***** PIPE JUNCTION CONTROL FLAGS

	CAHS	NR
4011101	0000	3
4021101	0000	2
4031101	0000	1

***** SNGLJUN, VALVE AND TMDPJUN GEOMETRY CARDS.

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*	FROM	TO	JUNAREA	FJUNF	FJUNR	CAHS
2510101	901000000	200010000	0.	0.0	0.0	0000
4500101	200000000	401000000	0.	0.0	0.0	0100
4510101	401010000	402000000	0.	0.0	0.0	0000
4520101	402010000	403000000	0.	0.0	0.0	0000
4530101	403010000	902000000	0.	0.0	0.0	0100

***** SNGLVOL AND PIPE VOLUME INITIAL CONDITIONS

*	CW	PRESSURE	QUAL	NR
2000200	2	5.0000E6	1.00	
4011201	2	5.0000E6	1.00	0. 0. 0. 4
4021201	2	5.0000E6	1.00	0. 0. 0. 3
4031201	2	5.0000E6	1.00	0. 0. 0. 2

***** TMDPVOL DATA CONTROL CARD

*	CW	TRIP	ALPHA	NUM
9010200	2	501		
9020200	2			

***** TMDPVOL DATA CARD

*	TIME	PRESS	QUAL
9010201	0.000	4981900.	1.000
9010202	.100	4927880.	1.000
9010203	.200	4866110.	1.000
9010204	.300	4829747.	1.000
9010205	.400	4794753.	1.000
9010206	.500	4747376.	1.000
9010207	.600	4718367.	1.000
9010208	.700	4691854.	1.000
9010209	.800	4657311.	1.000
9010210	.900	4637825.	1.000
9010211	1.000	4613516.	1.000
9010212	1.100	4600787.	1.000
9010213	1.200	4589881.	1.000
9010214	1.300	4575948.	1.000
9010215	1.400	4569016.	1.000
9010216	1.500	4565032.	1.000
9010217	1.600	4563218.	1.000
9010218	1.700	4563401.	1.000
9010219	1.800	4567248.	1.000
9010220	1.900	4572064.	1.000
9010221	2.000	4576934.	1.000
9010222	2.100	4584592.	1.000
9010223	2.200	4591024.	1.000
9010224	2.300	4600115.	1.000
9010225	2.400	4606497.	1.000
9010226	2.500	4613723.	1.000
9010227	2.600	4620684.	1.000
9010228	2.700	4623998.	1.000
9010229	2.800	4628821.	1.000
9010230	2.900	4634576.	1.000
9010231	3.000	4635503.	1.000
9010232	3.100	4636305.	1.000
9010233	3.200	4636456.	1.000
9010234	3.300	4635035.	1.000
9010235	3.400	4630834.	1.000
9010236	3.500	4626632.	1.000
9010237	3.600	4622737.	1.000
9010238	3.700	4619639.	1.000

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9010239	3.800	4616288.	1.000
9010240	3.900	4608276.	1.000
9010241	4.000	4603496.	1.000
9010242	5.000	4550326.	1.000
9010243	6.000	4483077.	1.000
9010244	7.000	4427020.	1.000
9010245	8.000	4362641.	1.000
9010246	9.000	4303644.	1.000
9010247	10.000	4248200.	1.000
9010248	11.000	4189435.	1.000
9010249	12.000	4132475.	1.000
9010250	13.000	4075548.	1.000
9010251	14.000	4020970.	1.000
9010252	15.000	3963155.	1.000
9010253	16.000	3918553.	1.000
9010254	18.000	3815226.	1.000
9010255	20.000	3727483.	1.000
9010256	22.000	3643477.	1.000
9010257	24.000	3556808.	1.000
9010258	26.000	3469451.	1.000
9010259	28.000	3381221.	1.000
9010260	30.000	3299092.	1.000
9010261	32.000	3218463.	1.000
9010262	34.000	3133862.	1.000
9010263	36.000	3058316.	1.000
9010264	38.000	2985187.	1.000
9010265	40.000	2921124.	1.000
9010266	42.000	2853242.	1.000
9010267	44.000	2784410.	1.000
9010268	46.000	2717872.	1.000
9010269	48.000	2663770.	1.000
9010270	50.000	2601918.	1.000
9010271	52.000	2538747.	1.000
9010272	54.000	2490818.	1.000
9010273	56.000	2430753.	1.000
9010274	58.000	2372546.	1.000
9010275	60.000	2326299.	1.000
9010276	62.000	2283809.	1.000
9010277	64.000	2223326.	1.000
9010278	66.000	2178751.	1.000
9010279	68.000	2135757.	1.000
9010280	70.000	2092031.	1.000
9010281	72.000	2050116.	1.000
9010282	74.000	2008471.	1.000
9010283	76.000	1965180.	1.000
9010284	78.000	1922647.	1.000
9010285	80.000	1901403.	1.000
9010286	82.000	1880158.	1.000
9010287	84.000	1880158.	1.000
9010288	85.000	1876141.	1.000
9010289	86.000	1868512.	1.000
9010290	87.000	1865495.	1.000
9010291	88.000	1872848.	1.000
9010292	89.000	1879907.	1.000
9010293	90.000	1880158.	1.000
9010294	95.000	1880158.	1.000

*
9020201 0. 0.100E6 1.
*

***** SNGLJUN AND VALVE INITIAL CONDITION CARD

1986-07-25

2510201	1	0.0	0.	0.
4500201	1	0.0	0.	0.
4510201	1	0.0	0.	0.
4520201	1	0.0	0.	0.
4530201	1	0.0	0.	0.

*

***** PIPE JUNCTION CONDITIONS CONTROL CARD

4011300 1

4021300 1

4031300 1

*

***** PIPE AND BRANCH JUNCTION INITIAL CONDITION CARD

4011301 0.0 0. 0. 3

4021301 0.0 0. 0. 2

4031301 0.0 0. 0. 1

*

***** VALVE TYPE CARD

4530300 TRPULV

*

***** VALVE DATA

4530301 501

*

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APPENDIX B

LISTING OF INPUT DATA FOR CASE CFT01

```
1  = MARVIKEN CFT 21. SUBCOLD CRIT FLOW. P,T BC AT VSL BOT.
2  *
3  *
4  0000100  NEW  TRANSNT
5  0000101  RUN
6  0000102  SI  SI
7  0000105  30.    40.
8  *
9  *
10 ***** TIME STEP CONTROL CARDS
11 *          END-TIME  DTMIN    DTMAX    OPT    MINOR  MAJOR  RESTART
12 0000201  30.00    1.0-6    .100    00003    1    50    50
13 *
14 ***** MINOR EDIT REQUESTS
15 301      P  901010000
16 303  CNTRLVAR 105    * RATIO (MEAS FLOW / CALC FLOW)
17 304  CNTRLVAR 110    * QUAL RING II EXP
18 305  QUALE 402020000 * CALC QUAL RING II
19 306  CNTRLVAR 122    * DP205  CALC-EXP
20 307  CNTRLVAR 130    * T - TSAT IN VOL 901
21 *
22 ***** TRIP INPUT DATA
23 0000501  TIME  0          GT  NULL    0    0.0  L  *
24 0000502  CNTRLVAR 130    GE  NULL    0    -0.1  L  *
25 *
26 *      STOP SUBCOOLED TRANSIENT WHEN T-TSAT GT -0.1K
27 *
28 600  502
29 *
30 *
31 *
32 ***** HYDRAULIC COMPONENTS
33 *
34 *****
35 *
36 4020000  DPIPE      PIPE      * -0.690 TO -5.570
37 *4030000  NOZZLE     PIPE      * -5.570 TO -6.565
38 9010000  P-T(BC)    TMDPVOL
39 9020000  ATMOS      TMDPVOL
40 *
41 *
42 *      JUNCTIONS
43 *
44 4510000  DISCH-IN    SNGLJUN
45 *4520000  NOZZ-IN     SNGLJUN
46 4530000  NOZZ-OUT    VALVE
47 *
48 *
49 ***** COMPONENT INFORMATION CARDS
50 4020001  3
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```

51 +4030001 5
52 *
53 ***** SNGLVOL, BRANCH AND TMDPVOL GEOMETRY CARDS
54 *
55 * AREA LENGTH VOLUME HA VANG ELEVCH ROUGH DIAH FE
56 9010101 19.6 0.5 0.0 0. -90. .000 20.-6 .0 00
57 9020101 0. 1. 1. 0. -90. .000 20.-6 .0 00
58 *
59 ***** PIPE AND ANNULUS GEOMETRY CARDS
60 *
61 * VOLAREA NR
62 4020101 0.4441 3 * D = 0.752
63 +4030101 0.07022 5 * D = 0.299
64 *
65 * LENGTH NR
66 4020301 2.100 3 * 6.3 /3
67 +4030301 0.236 5 * 1.180/5
68 *
69 * VOLUME NR
70 4020401 0.00000 3
71 +4030401 0.00000 5
72 *
73 * VANG NR
74 4020601 -90. 3
75 +4030601 -90. 5
76 *
77 * ROUGH DIAH NR
78 4020801 20.E-6 0.0 3
79 +4030801 20.E-6 0.0 5
80 *
81 *** PIPE JUNCTION LOSS COEFFICIENTS
82 * FORWARD REVERSE NR
83 4020901 0.00 0.00 2
84 +4030901 0.00 0.00 4
85 * FE NR
86 4021001 00 3
87 +4031001 00 5
88 *
89 ***** PIPE JUNCTION CONTROL FLAGS
90 * CAHS NR
91 4021101 0000 2
92 +4031101 0000 4
93 *
94 ***** SNGLJUN, VALVE AND TMDPJUN GEOMETRY CARDS
95 *
96 * FROM TO JUNAREA FJUNF FJUNR CAHS
97 4510101 901000000 402000000 0. 0.0 0.0 0000
98 +4520101 402010000 403000000 0. 0.0 0.0 0000
99 4530101 402010000 902000000 0.1963 0.0 0.0 0100
100 *
101 ***** SNGLVOL AND PIPE VOLUME INITIAL CONDITIONS
102 *
103 * CW PRESSURE QUAL NR
104 4021201 3 4.2131E6 508.54 0. 0. 0. 3
105 +4031201 2 5.0000E6 1.00 0. 0. 0. 5
106 *
107 ***** TMDPVOL DATA CONTROL CARD
108 * CW TRIP ALPHA NUM
109 *
110 ***** CFT21 PRESSURE AND TEMPERATURE AT BOTTOM OF VESSEL *****

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```
111 ***** PRESSURE FROM 001M106.  TEMP FROM AVG OF 001M521 AND 001M402
112 *
113 9010200 3 501
114 9010201 .00 .509680E+07 503.46
115 9010202 .50 .425960E+07 501.31
116 9010203 1.00 .481560E+07 502.01
117 9010204 1.50 .487560E+07 503.31
118 9010205 2.00 .474530E+07 503.11
119 9010206 2.50 .467900E+07 504.01
120 9010207 3.00 .457180E+07 504.11
121 9010208 3.50 .451670E+07 504.01
122 9010209 4.00 .443460E+07 503.21
123 9010210 4.50 .439870E+07 504.21
124 9010211 5.00 .435300E+07 504.61
125 9010212 5.50 .429500E+07 504.46
126 9010213 6.00 .425320E+07 504.86
127 9010214 6.50 .421590E+07 505.31
128 9010215 7.00 .413030E+07 505.01
129 9010216 7.50 .412930E+07 505.26
130 9010217 8.00 .405310E+07 505.56
131 9010218 8.50 .405760E+07 505.71
132 9010219 9.00 .402270E+07 505.71
133 9010220 9.50 .399420E+07 505.71
134 9010221 10.00 .391990E+07 505.71
135 9010222 10.50 .390030E+07 505.71
136 9010223 11.00 .385400E+07 505.76
137 9010224 11.50 .381230E+07 505.71
138 9010225 12.00 .378470E+07 505.71
139 9010226 12.50 .373310E+07 505.71
140 9010227 13.00 .367460E+07 506.01
141 9010228 13.50 .367360E+07 505.76
142 9010229 14.00 .364710E+07 505.96
143 9010230 14.50 .361170E+07 506.06
144 9010231 15.00 .357140E+07 506.36
145 9010232 15.50 .353010E+07 506.06
146 9010233 16.00 .352910E+07 506.01
147 9010234 16.50 .350600E+07 506.16
148 9010235 17.00 .350400E+07 506.16
149 9010236 17.50 .343420E+07 506.01
150 9010237 18.00 .340910E+07 506.41
151 9010238 18.50 .339340E+07 506.26
152 9010239 19.00 .337180E+07 506.51
153 9010240 19.50 .335560E+07 506.66
154 9010241 20.00 .333930E+07 506.66
155 9010242 20.50 .330200E+07 506.76
156 9010243 21.00 .328380E+07 506.66
157 9010244 21.50 .327840E+07 506.76
158 9010245 22.00 .326950E+07 506.66
159 9010246 22.50 .324540E+07 506.71
160 9010247 23.00 .320660E+07 506.26
161 9010248 23.50 .323270E+07 506.76
162 9010249 24.00 .321400E+07 506.71
163 9010250 24.50 .320710E+07 506.96
164 9010251 25.00 .319280E+07 506.71
165 9010252 25.50 .312160E+07 506.96
166 9010253 26.00 .314810E+07 507.21
167 9010254 26.50 .314610E+07 507.46
168 9010255 27.00 .312890E+07 507.41
169 9010256 27.50 .311980E+07 508.16
170 9010257 28.00 .308910E+07 507.31
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171 9010258 28.50 .310730E+07 507.56
172 9010259 29.00 .309650E+07 507.66
173 9010260 29.50 .310880E+07 507.81
174 9010261 30.00 .309500E+07 507.26
175 *
176 *
177 *
178 9020200 2
179 9020201 0. 0.100E6 1.
180 *
181 ***** SNGLJUN AND VALVE INITIAL CONDITION CARD
182 4510201 1 0.0 0. 0.
183 *4520201 1 0.0 0. 0.
184 4530201 1 0.0 0. 0.
185 *
186 ***** PIPE JUNCTION CONDITIONS CONTROL CARD
187 4021300 1
188 *4031300 1
189 *
190 ***** PIPE AND BRANCH JUNCTION INITIAL CONDITION CARD
191 4021301 0.0 0. 0. 2
192 *4031301 0.0 0. 0. 4
193 *
194 ***** VALVE TYPE CARD
195 4530300 TRPULV
196 *
197 ***** VALVE DATA
198 4530301 501
199 *
200 *
201 * CONTROL COMPONENT 101, EXPERIMENTAL MASSFLOW
202 20510100 NOZZFLOW-X FUNCTION 1. 0. 0
203 20510101 TIME 0 801
204 *
205 * CONTROL COMPONENT 102, CALC - EXP CRITICAL FLOW
206 20510200 FLOWERR SUM 1. 0. 0
207 20510201 0. 1. MFLOWJ 453000000
208 20510202 -1. CNTRLVAR 101
209 *
210 * CONTROL COMPONENT 103, REL.ERR. OF CRITICAL FLOW
211 20510300 CF-REL-ERR DIV 100. 0. 0
212 20510301 CNTRLVAR 101 CNTRLVAR 102
213 *
214 * CONTROL COMPONENT 104, COMPUTED MASSFLOW
215 20510400 NOZZFLOW-C SUM 1. 0.0001 0
216 20510401 0.0001 1. MFLOWJ 453000000
217 *
218 * CONTROL COMPONENT 105, RATIO
219 20510500 CF-RATIO DIV 1. 1. 0
220 20510501 CNTRLVAR 104 CNTRLVAR 101
221 *
222 * GENERAL TABLE USED BY CONTROL COMPONENT 101
223 * MASS FLOW FROM CFT 21 ( FROM FILE T21EVAL, VARNAM=FAVE)
224 *
225 * GENERAL TABLE 801. MEASURED DISCHARGE FLOW RATE (FAVE)
226 *
227 20280100 REAC-T
228 20280101 .00 11000.00
229 20280102 1.00 10634.00
230 20280103 2.00 10632.00

```

231	20280104	3.00	10063.00
232	20280105	4.00	9791.20
233	20280106	5.00	9281.40
234	20280107	6.00	9125.90
235	20280108	7.00	8815.60
236	20280109	8.00	8377.10
237	20280110	9.00	8493.10
238	20280111	10.00	8162.90
239	20280112	11.00	7937.20
240	20280113	12.00	7622.30
241	20280114	13.00	7262.10
242	20280115	14.00	7138.30
243	20280116	15.00	6771.10
244	20280117	16.00	6718.70
245	20280118	17.00	6468.00
246	20280119	18.00	6439.30
247	20280120	19.00	6261.30
248	20280121	20.00	6175.60
249	20280122	21.00	6127.90
250	20280123	22.00	5880.20
251	20280124	22.50	5789.90
252	20280125	23.00	5737.50
253	20280126	23.50	5519.70
254	20280127	24.00	5443.80
255	20280128	24.50	5212.50
256	20280129	25.00	5106.70
257	20280130	25.50	4774.20
258	20280131	26.00	4632.10
259	20280132	26.50	4381.10
260	20280133	27.00	4299.60
261	20280134	27.50	4075.40
262	20280135	28.00	3887.80
263	20280136	28.50	3896.40
264	20280137	29.00	3800.80
265	20280138	29.50	3685.00
266	20280139	30.00	3555.90
267	20280140	30.50	3652.90
268	20280141	31.00	3450.10
269	20280142	31.50	3450.00
270	20280143	32.00	3359.50
271	20280144	32.50	3253.00
272	20280145	33.00	3272.70
273	20280146	33.50	3133.70
274	20280147	34.00	2832.30
275	20280148	34.50	2926.90
276	20280149	35.00	3005.70
277	20280150	35.50	2900.70
278	20280151	36.00	2962.60
279	20280152	36.50	3359.50
280	20280153	37.00	3373.30
281	20280154	37.50	3381.90
282	20280155	38.00	3297.10
283	20280156	38.50	3338.60
284	20280157	39.00	3204.70
285	20280158	39.50	3251.80
286	20280159	40.50	2812.30
287	20280160	41.50	2940.70
288	20280161	42.50	2936.30
289	20280162	43.50	2694.00
290	20280163	44.50	2646.10

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291	20280164	45.50	2634.00
292	20280165	46.50	2823.30
293	20280166	47.50	2745.90
294	20280167	48.50	2728.10
295	20280168	49.50	2604.40
296	20280169	50.50	2715.10
297	20280170	51.50	2500.30
298	20280171	52.50	2695.40
299	20280172	53.50	2692.30
300	20280173	54.50	2634.60
301	20280174	55.50	2481.00
302	20280175	56.50	2491.70
303	20280176	57.50	2458.00
304	20280177	58.50	2542.70
305	20280178	59.50	2467.70
306	*		
307	* CONTROL COMPONENT 110. EXPERIMENTAL CALCULATED QUAL AT RING II		
308	20511000	X-RINGII FUNCTION 1. 0. 0	
309	20511001	TIME 0 803	
310	*		
311	*		
312	* GENERAL TABLE 803. QUALITY AT RING II (XGAV)		
313	20280300	REAC-T	
314	20280301	.00	.000000
315	20280302	1.00	.000000
316	20280303	2.00	.000000
317	20280304	3.00	.000000
318	20280305	4.00	.000000
319	20280306	5.00	.000000
320	20280307	6.00	.000000
321	20280308	7.00	.000000
322	20280309	8.00	.000000
323	20280310	9.00	.000000
324	20280311	10.00	.000000
325	20280312	11.00	.000000
326	20280313	12.00	.000000
327	20280314	13.00	.000000
328	20280315	14.00	.000000
329	20280316	15.00	.000000
330	20280317	16.00	.000000
331	20280318	17.00	.000000
332	20280319	18.00	.000000
333	20280320	19.00	.000000
334	20280321	20.00	.000000
335	20280322	21.00	.000000
336	20280323	22.00	.00013
337	20280324	22.50	.000000
338	20280325	23.00	.000005
339	20280326	23.50	.00016
340	20280327	24.00	.00037
341	20280328	24.50	.00046
342	20280329	25.00	.00055
343	20280330	25.50	.00099
344	20280331	26.00	.00147
345	20280332	26.50	.00161
346	20280333	27.00	.00176
347	20280334	27.50	.00193
348	20280335	28.00	.00182
349	20280336	28.50	.00206
350	20280337	29.00	.00223

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351	20280338	29.50	.00237
352	20280339	30.00	.00263
353	20280340	30.50	.00237
354	20280341	31.00	.00247
355	20280342	31.50	.00262
356	20280343	32.00	.00267
357	20280344	32.50	.00282
358	20280345	33.00	.00316
359	20280346	33.50	.00348
360	20280347	34.00	.00365
361	20280348	34.50	.00377
362	20280349	35.00	.00400
363	20280350	35.50	.00381
364	20280351	36.00	.00416
365	20280352	36.50	.00430
366	20280353	37.00	.00445
367	20280354	37.50	.00443
368	20280355	38.00	.00468
369	20280356	38.50	.00473
370	20280357	39.00	.00474
371	20280358	39.50	.00605
372	20280359	40.50	.00793
373	20280360	41.50	.00979
374	20280361	42.50	.01141
375	20280362	43.50	.01181
376	20280363	44.50	.01193
377	20280364	45.50	.01251
378	20280365	46.50	.01245
379	20280366	47.50	.01217
380	20280367	48.50	.01228
381	20280368	49.50	.01205
382	20280369	50.50	.01175
383	20280370	51.50	.01213
384	20280371	52.50	.01152
385	20280372	53.50	.01274
386	20280373	54.50	.01293
387	20280374	55.50	.01364
388	20280375	56.50	.01369
389	20280376	57.50	.01316
390	20280377	58.50	.01347
391	20280378	59.50	.01358
392	*		
393	*		
394	*	CONTROL COMPONENT 120. EXPERIMENTAL DP205. RINGI TO VESL BOT	
395	*		
396	20512000	DP205MEAS FUNCTION 1. 0. 0	
397	20512001	TIME 0 802	
398	*		
399	*	CONTROL COMPONENT 121. CALC DP 205.	
400	20512100	DP205CALC SUM 1. 0. 0	
401	20512101	0. 1. P 402020000	
402	20512102	-1. P 901010000	
403	*		
404	*		
405	*	CONTROL COMPONENT 122. CALC MINUS MEAS DP205	
406	20512200	DIFFDP205 SUM 1. 0. 0	
407	20512201	0. 1. CNTRLVAR 121	
408	20512202	-1. CNTRLVAR 120	
409	*		
410	*		

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411 * GENERAL TABLE 802. DP205 (RING1 TO VESSEL BOTTOM) 001M205
412 *
413 20280200 REAC-T
414 20280201 .00 .596140E+04
415 20280202 1.00 -.407560E+06
416 20280203 2.00 -.376360E+06
417 20280204 3.00 -.355610E+06
418 20280205 4.00 -.306570E+06
419 20280206 5.00 -.305870E+06
420 20280207 6.00 -.279860E+06
421 20280208 7.00 -.231390E+06
422 20280209 8.00 -.229750E+06
423 20280210 9.00 -.221960E+06
424 20280211 10.00 -.213740E+06
425 20280212 11.00 -.190830E+06
426 20280213 12.00 -.189630E+06
427 20280214 13.00 -.177610E+06
428 20280215 14.00 -.172230E+06
429 20280216 15.00 -.153120E+06
430 20280217 16.00 -.148750E+06
431 20280218 17.00 -.147300E+06
432 20280219 18.00 -.137490E+06
433 20280220 19.00 -.131160E+06
434 20280221 20.00 -.120660E+06
435 20280222 21.00 -.115030E+06
436 20280223 22.00 -.112490E+06
437 20280224 22.50 -.109900E+06
438 20280225 23.00 -.102120E+06
439 20280226 23.50 -.962950E+05
440 20280227 24.00 -.101420E+06
441 20280228 24.50 -.891450E+05
442 20280229 25.00 -.876260E+05
443 20280230 25.50 -.697820E+05
444 20280231 26.00 -.759200E+05
445 20280232 26.50 -.711110E+05
446 20280233 27.00 -.602270E+05
447 20280234 27.50 -.581390E+05
448 20280235 28.00 -.540890E+05
449 20280236 28.50 -.465590E+05
450 20280237 29.00 -.457360E+05
451 20280238 29.50 -.432690E+05
452 20280239 30.00 -.427620E+05
453 20280240 30.50 -.383330E+05
454 20280241 31.00 -.404840E+05
455 20280242 31.50 -.368140E+05
456 20280243 32.00 -.399780E+05
457 20280244 32.50 -.350430E+05
458 20280245 33.00 -.327650E+05
459 20280246 33.50 -.342200E+05
460 20280247 34.00 -.364350E+05
461 20280248 34.50 -.379530E+05
462 20280249 35.00 -.356750E+05
463 20280250 35.50 -.360550E+05
464 20280251 36.00 -.358020E+05
465 20280252 36.50 -.381430E+05
466 20280253 37.00 -.378270E+05
467 20280254 37.50 -.372570E+05
468 20280255 38.00 -.376370E+05
469 20280256 38.50 -.375100E+05
470 20280257 39.00 -.378270E+05

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471 20280258 39.50 -.361820E+05
472 20280259 40.50 -.393450E+05
473 20280260 41.50 -.377000E+05
474 20280261 42.50 -.370040E+05
475 20280262 43.50 -.363080E+05
476 20280263 44.50 -.353590E+05
477 20280264 45.50 -.355490E+05
478 20280265 46.50 -.345360E+05
479 20280266 47.50 -.364350E+05
480 20280267 48.50 -.373210E+05
481 20280268 49.50 -.365610E+05
482 20280269 50.50 -.355490E+05
483 20280270 51.50 -.349160E+05
484 20280271 52.50 -.343460E+05
485 20280272 53.50 -.340300E+05
486 20280273 54.50 -.347260E+05
487 20280274 55.50 -.346630E+05
488 20280275 56.50 -.367510E+05
489 20280276 57.50 -.341570E+05
490 20280277 58.50 -.320050E+05
491 20280278 59.50 -.319420E+05
492 * CONTROL COMP 130. T901-TSAT901
493 * USE THIS CONTROL VARIABLE TO END SUBCOOLED B.C TRANSIENT
494 20513000 T-TSAT901 SUM 1. -34. 1
495 20513001 0. 1. TEMPF 901010000
496 20513002 -1. SATTEMP 901010000
497 *
498 .
```

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APPENDIX C

LISTING OF INPUT DATA FOR CASE CFT04

```

1  *
2  = MARVIKEN CFT 21. SAT CRIT FLOW. P,X BC AT VSL BOT.
3  * ROBTASME0FGCFT810( SUBCOOLED RUN WITH CD=0.85, AND T901 INCREASED 2K
7  *
8  *
9  *
10 0000100 RESTART TRANSIT
11 0000101 RUN
12 0000102 SI SI
13 103 387
14 0000105 30. 40.
15 *
16 *
17 ***** TIME STEP CONTROL CARDS
18 * END-TIME DTMIN DTMAX OPT MINOR MAJOR RESTART
20 2020201 6030.00 1.E+50-6 0.1 .020 00000003 315 1002 1002
21 *
22 ***** MINOR EDIT REQUESTS
23 301 P 901010000
24 303 CNTRLVAR 105 * RATIO (MEAS FLOW / CALC FLOW)
25 304 CNTRLVAR 110 * QUAL RING II EXP
26 305 QUALE 402020000 * CALC QUAL RING II
27 306 CNTRLVAR 122 * DP205 CALC-EXP
28 *
29 ***** TRIP INPUT DATA
30 0000502 TIME 0 GE NULL 0 60.0 L *
31 *
32 * INPUT P,X BC AT VOL 901.
33 9010000 P-X(BC) TMDPVOL
34 9010101 19.6 0.5 0.0 0. -90. 0.000 20.-6 0. 00
35 *
36 *
37 *
38 ***** CFT 21 PRESSURE AND QUALITY AT BOTTOM OF VESSEL *****
39 * P FROM 001M106 X FROM XV6B
40 *
41 *
42 ***** CFT 21 PRESSURE AND QUALITY AT BOTTOM OF VESSEL *****
43 * P FROM 001M106 X FROM XV6B
44 *
45 9010200 2 501
46 9010201 0.0 3.13406E6 0.0
47 9010202 25.00 .313406E+07 .00000
48 9010203 25.50 .313406E+07 .00000
49 9010204 26.00 .313406E+07 .00000
50 9010205 26.50 .313406E+07 .00000
51 9010206 27.00 .312890E+07 .00000
52 9010207 27.50 .311990E+07 .00000
53 9010208 28.00 .308910E+07 .00000
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55 9010210 29.00 .309650E+07 .00046

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64	9010219	33.50	.304190E+07	.00238
65	9010220	34.00	.302770E+07	.00245
66	9010221	34.50	.302620E+07	.00259
67	9010222	35.00	.303010E+07	.00282
68	9010223	35.50	.301040E+07	.00277
69	9010224	36.00	.300600E+07	.00267
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74	9010229	38.50	.298640E+07	.00340
75	9010230	39.00	.297460E+07	.00359
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82	9010237	42.50	.292540E+07	.00975
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89	9010244	46.00	.287770E+07	.01105
90	9010245	46.50	.287000E+07	.01120
91	9010246	47.00	.285260E+07	.01103
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93	9010248	48.00	.284040E+07	.01077
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95	9010250	49.00	.280250E+07	.01107
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97	9010252	50.00	.280450E+07	.01071
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99	9010254	51.00	.279070E+07	.01062
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111	9010266	57.00	.268250E+07	.01262
112	9010267	57.50	.267070E+07	.01181
113	9010268	58.00	.265550E+07	.01195
114	9010269	58.50	.263880E+07	.01193
115	9010270	59.00	.264170E+07	.01217

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116	9010271	59.50	.262050E+07	.01226
117	9010272	60.00	.261370E+07	.01245
118	.			

NRC FORM 325 (2-84) NRCM 1102, 3201, 3202 BIBLIOGRAPHIC DATA SHEET SEE INSTRUCTIONS ON THE REVERSE		U.S. NUCLEAR REGULATORY COMMISSION		1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any) NUREG/IA-0007 STUDSVIK/NP-86/99	
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5. AUTHOR(S) Ö. Rosdahl, D. Caraher				4. DATE REPORT COMPLETED MONTH YEAR	
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12. SUPPLEMENTARY NOTES				11a. TYPE OF REPORT Technical b. PERIOD COVERED (inclusive dates)	
13. ABSTRACT (200 words or less) RELAP5/MOD2 simulations of the critical flow of saturated steam are reported together with simulations of the critical flow of subcooled liquid and low-quality two-phase mixture. The experiments which were simulated used nozzle diameters of 0.3 m and 0.5 m. RELAP5 overpredicted the experimental flow rates by 10 to 25 percent unless discharge coefficients were applied.					
14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS RELAP5/MOD2 Marviken test critical flow of saturated steam ICAP code assessment b. IDENTIFIERS/OPEN-ENDED TERMS				15. AVAILABILITY STATEMENT Unlimited 16. SECURITY CLASSIFICATION (This page) Unclassified (This report) Unclassified 17. NUMBER OF PAGES 18. PRICE	

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ASSESSMENT OF RELAP5/MOD 2 AGAINST CRITICAL FLOW DATA FROM
MARVIKEN TESTS J1T II AND CFT 21

SEPTEMBER 1986